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HEAT TRANSMISSION THROUGH BOILER TUBES

BY

HENRY KREISINGER AND J. F. BARKLEY

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HEAT TRANSMISSION THROUGH BOILER TUBES.

By Henry Kreisinger and J. F. Barkley.

INTRODUCTION.

This report is one of a series of publications of the Bureau of Mines on the general subject of the transmission of heat in boiler plants. The first of these publications, Bulletin 8, entitled "The Flow of Heat Through Furnace Walls," treats of the heat losses through furnace walls of different materials and construction. The second publication, Bulletin 18, entitled "The Transmission of Heat Into Steam Boilers," treats chiefly of the impartation of heat from the hot products of combustion to the heating plates of a boiler. This report, the third of the series, presents the results of a study of the transmission of heat through the metal of the heating plate, the temperatures of the surfaces of the plate being measured while the boiler is in operation. A large number of temperature determinations were made of both surfaces of a tube of a Heine boiler, and while these temperatures were being determined, the average rate of evaporation was obtained by measuring the water fed to the boiler. The relations between the temperatures were studied by means of charts. The deductions from these studies can be briefly stated as follows:

The temperature drop from the hot products of combustion to the tube of the boiler is high, whereas that through the metal of the tube itself and from the metal to the boiler water is low. In other words, the metal of the boiler tube is nearly at the same temperature as the boiler water. The temperatures also indicate that as long as the water side of the heating plate is free from scale, oil, or other deposit the metal of the boiler tubes can not be overheated, even though the boiler is worked at several times its rated capacity.

HOW HEAT IS TRANSMITTED INTO BOILER WATER.

The path of heat transmission from the hot products of combustion and the hot fuel bed into the boiler water is divisible into three distinct parts, and each of these parts must be thoroughly understood before any intelligent study of the heat transmission can be made. The diagram of the path in figure 1, which shows a cross section of a

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boiler plate with water on one side and hot gases and burning fuel on the other, will help to give a clear conception of the three parts.

For the sake of simplicity the plate is considered free from soot and scale.

The first part of the path of heat travel extends from the hot products of combustion and hot fuel bed to the gas-side surface of the boiler plate. Over this part of the path the heat travels by convection from the hot gases and by radiation from the hot fuel and flames. In modern steam boilers only a small part of the heating plates receives heat by radiation, most of the heat received being imparted by the hot products of combustion, so that convection becomes the most important mode of heat propagation. The diagram

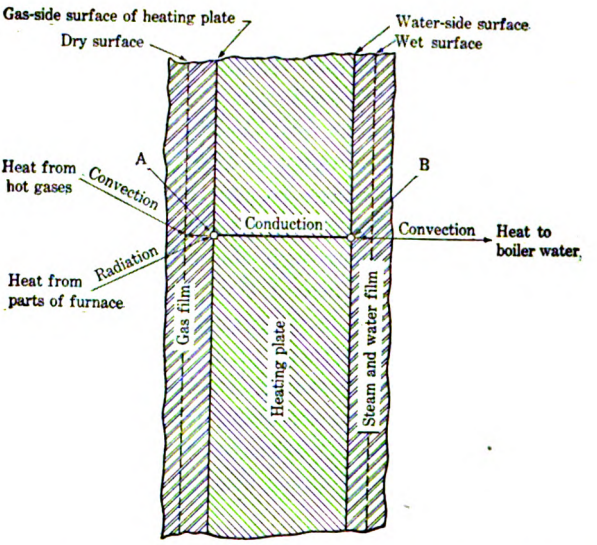

FIGURE 1.—Diagram showing the path of heat travel from the hot gases through the heating plate into the boiler water.

shows that convection stops at the dry surface in the film of gas near the plate, whereas radiation penetrates this film of gas and ceases at the surface of the solid material, which in the diagram is the gas-side surface of the heating plate. This penetration of the radiant heat directly to the solid material is due to the fact that gases are largely permeable to radiation. Bulletin 18[a] is devoted mainly to the detailed study of this first part of the heat path.

The second part of the path extends from the dry surface of the heating plate to the wet surface. Over this part of the path the heat is shown to pass by conduction. This second part of the heat

[a] Kreisinger, Henry, and Ray, W. T., The transmission of heat into steam boilers: Bull. 18, Bureau of Mines, 1912, 180 pp.

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path has been briefly discussed in Bulletin 18.[a] However, as no experimental data were then available, the discussion was purely a mathematical one. It is gratifying that the values obtained mathematically are substantiated by the experimental results presented in this publication. It is with the mode of heat transmission through this part of the path that the present bulletin chiefly deals.

The third part of the path extends from the wet surface to the boiler water, and along it the heat passes mainly by convection. Thus the heat from the fire changes its mode of travel twice before it reaches the water in the boiler, and the three parts of its path are natural and not arbitrary divisions.

The mode of heat travel in each part of the path is governed by laws that differ widely, and no one of the laws will fit the whole path of the heat travel. This fact must be realized in any heat-transmission investigation if the results and conclusions are to have any practical value.

The three modes of heat propagation and the laws governing them are discussed in detail in Bulletin 18.[b] In this report are given only brief statements of the three modes and the laws governing them.

RADIATION.

Radiation is that mode of heat propagation by which heat passes from one body to another without the aid of any material agency. In the case of a furnace and the heating plate of a boiler, the heat from the hot fuel bed and furnace walls flows by radiation through the space filled with gases, directly to the boiler plate, without heating the gases appreciably.

The quantity of heat that is transmitted from the hot parts of the furnace to the boiler plate is closely proportional to the difference between the fourth powers of the absolute temperatures of the hot parts of the furnace and the boiler plate.

CONVECTION.

Convection of heat always implies the motion of a fluid receiving or giving up the heat. In the case of the hot gases and the boiler, heat is transferred to the heating plate by small particles of gas moving from the body of the gas toward the plate and imparting their heat to the plate when they touch it. In other words, convection of heat on the gas side of the heating plate is a continuous interchange of the cooled particles of gas next to the surface with the hot ones farther away within the body of the gas. On the water side of the heating plate convection is continuous exchange of hot water and

[a] Kreisinger, Henry, and Ray, W. T., Op. cit., pp. 103–106.
[b] Kreisinger, Henry, and Ray, W. T., Op. cit., pp. 103–135.

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bubbles of steam next to the plate with water farther away in the boiler.

Within wide limits the heat transmitted from the hot gases to the dry surface of the heating plate is proportional to three main factors, (1) the difference between the temperatures of the hot gases and the dry surface of the heating plate, (2) the velocity of the hot gases moving over the dry surface, and (3) the density of the hot gases.

CONDUCTION.

Conduction of heat is the process by which heat flows from a hotter body to a colder one when the two bodies are in contact; or from a hotter to a colder part of the same body. In a boiler the heat passes by conduction from the particles of hot gas in touch with the heating plate into the plate and through the metal into the water in contact with the wet surface of the heating plate.

The quantity of heat which can be transmitted through a unit area of heating plate in a unit of time is proportional to the difference of temperature between the dry and the wet surfaces of the plate, proportional to the conductivity of the plate, and inversely proportional to the thickness of the plate. This law can be expressed by the following simple formula:

$$H \propto \frac{C}{d}(t_1 - t)$$

in which H = the quantity of heat transmitted per unit of area of heating plate,
C = the average heat conductivity of the material between the dry and the wet surfaces,
d = the distance between the dry and wet surfaces,
t_1 = the temperature of the dry surface, and
t = the temperature of the wet surface.

The investigations reported in this paper cover only that part of the heat path which extends through the metal of the heating plate. This part of the path is represented in figure 1 by the heavy line AB. It is to be remembered that this is not the entire part of the path over which heat travels by conduction. As explained in Bulletin 18,[a] the conduction starts in a film of gas a very short distance from the metal plate and stops within the film of water and steam at a similarly short distance.

DEFINITION OF HEATING PLATE AND SURFACES.

In this publication, as in Bulletin 18, the term "heating plate" is used in place of the conventional term "heating surface." In order to avoid confusion the word "surface" is reserved for the two sur-

[a] Kreisinger, Henry, and Ray, W. T., The transmission of heat into steam boilers: Bull. 18, Bureau of Mines, 1912, p. 20.

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faces of the plate which are termed "the gas-side surface" and the "water-side surface" of the heating plate. By the gas-side surface of the heating plate is understood the very thin layer of metal coming in contact with the gas; and by the water-side surface, the very thin layer of metal coming in contact with the water and steam. It is the temperature of these two surfaces that has been determined and is discussed in this bulletin. These two surfaces are somewhat different from "the dry surface" and "the wet surface" defined in Bulletin 18.[a] The "dry surface" of the heating plate is assumed to be the thin layer of gas near or at the outside surface of the heating plate or soot coating, where the heat ceases to travel by convection and starts to travel by conduction. The "wet surface" of the heating plate is assumed to be a thin layer of steam and water near or at the surface of the plate or layer of scale where the heat ceases to travel by conduction and starts to travel by convection. It is very difficult, if not impossible, to measure the temperature of the "dry surface" and the "wet surface." However, as the water-side surface of the heating plate is only a few degrees hotter than the boiler water, the temperature of the "wet surface" is probably very close to that of the water-side surface of the plate. With a clean boiler the "dry surface" is probably only a few degrees hotter than the gas-side surface of the heating plate.

METHOD OF MEASURING TEMPERATURE OF BOILER TUBES.

A large number of temperature determinations of both surfaces of a boiler tube were made while the boiler was under operation.

DESCRIPTION OF BOILER.

The boiler used in these determinations was a 2-pass Heine water-tube boiler rated at 210 boiler horsepower and was a part of the steam-plant equipment of the experiment station of the Bureau of Mines at Pittsburgh, Pa. It is the same boiler on which the steaming tests reported in Bulletin 23[b] were made. Under this boiler were discharged hot products of combustion from an experimental furnace having a combustion chamber about 40 feet long. Three horizontal baffles were so arranged that the gases passed twice among the boiler tubes and out through the uptake without coming in contact with the steam drum except in the rear for a length of about 3 feet. The furnace and the ash-pit door were sealed and the top of the bridge wall was tight against the lower row of tubes. The setting of the boiler and its connection to the experimental furnace is shown in figure 2.

[a] Kreisinger, Henry, and Ray, W. T., Op. cit., p. 20.

[b] Breckenridge, L. P., Kreisinger, Henry, and Ray, W. T., Steaming tests of coals and related investigations, September 1, 1904, to December 31, 1908: Bull. 23, Bureau of Mines, 1912, 380 pp.

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POSITION OF THERMOCOUPLES.

The temperature of the boiler tubes was measured with thermocouples. Several of these were embedded in the metal of a tube in the bottom row, at a point where the hot products of combustion enter among the tubes. One couple was placed in a tube in the highest row of tubes, at a point where the gases leave the boiler.

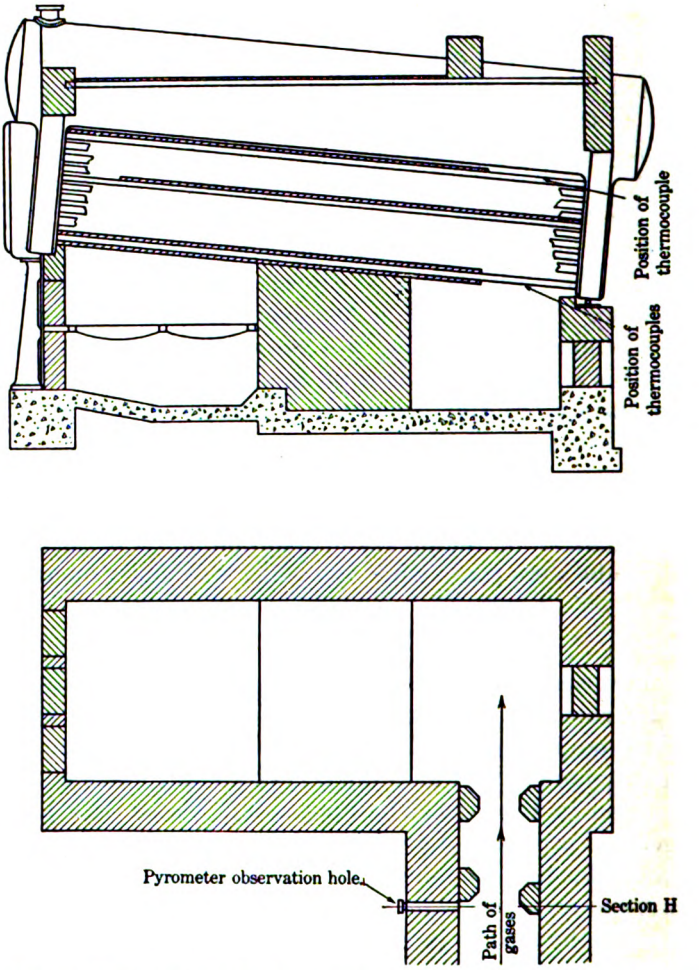

FIGURE 2.—Elevation of boiler and setting, position of thermocouples, and plan of setting.

The position of these couples is shown in figure 2. The first series of measurements was made with a platinum and platinum-rhodium couple on the outside of the fifth tube of the bottom row, one Hoskins nickel and nickel-chrome couple on the inside of the same tube, and a copper-constantan couple in a tube in the highest row.

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In the second series the Hoskins couple inside of the bottom-row tube was replaced with three copper-constantan couples, one of these being used to measure the temperature difference between the inside surface of the tube and the water in the boiler.

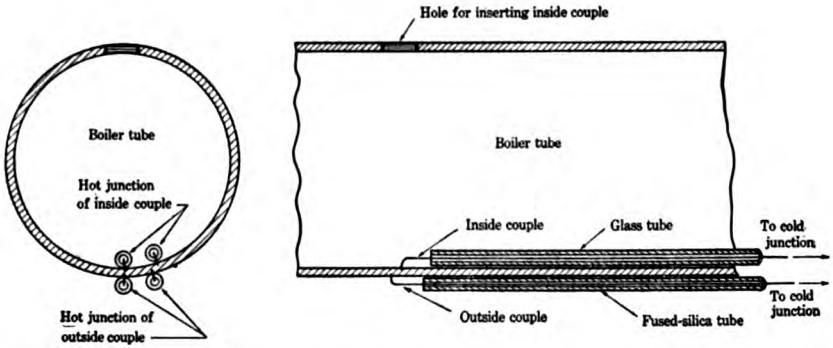

FIGURE 3.—Method of making hot junctions for measuring temperature of surfaces of heating plates. Each wire of a couple is embedded separately in the metal.

METHOD OF EMBEDDING THERMOCOUPLE WIRES IN BOILER TUBE.

Figure 3 illustrates the method of making the hot junctions of the couples used in measuring the temperatures of the inside and the outside surface of the boiler tubes. The junctions were formed by embedding both wires of each couple separately in the metal of the tube. The method of embedding the wires is shown in figure 4. A hole, about 0.001 inch larger in diameter than the wire, was drilled in the tube to the depth of about one-sixteenth inch, and the end of the wire was peened in with a special hollow tool having a cup-shaped end as shown in figure 4. The wire passed through the peening tool and was bent aside through the groove at the top of the tool so that the hammer did not strike the wire. Two or three light blows with an 8-ounce hammer were sufficient to peen the wire in the tube so tight that the wire would break rather than pull out of the hole. This method of peening the wire into the metal of the

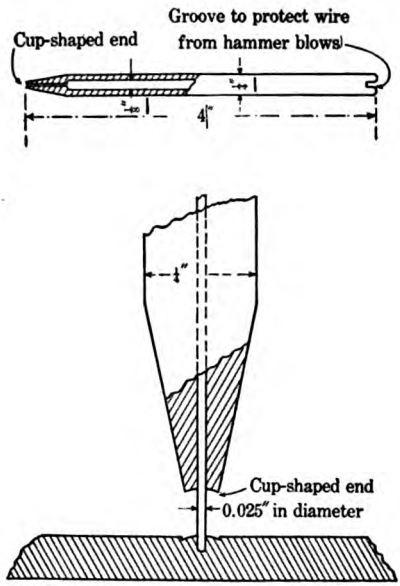

FIGURE 4.—Tool for embedding ends of thermocouple wires in heating plate and method of using tool.

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tube was developed by W. F. Hausstein, in charge of the instrument shop of the Pittsburgh station, Bureau of Mines.

The two wires of each couple make a junction through the metal of the tube and the couple measures the temperature of an infinitesimal layer of metal at the surface of the tube no matter how deep the end of the wire is bedded in the wall of the tube. This important feature is discussed more fully on page 25 to 28.

METHOD OF INSULATING AND LEADING WIRES OUT OF BOILER.

The couple wires on the inside of the tube were insulated from the boiler with glass tubing, and the couple wires on the outside with fused silica tubing, the latter being fastened to the boiler tube with a nickel wire band. In the first series of temperature measurements the wires of the inside couple were led out of the boiler through a handhole between two gaskets on the handhole cover. In addition to the gaskets the part of the wires passing through the handhole was covered with $\frac{1}{8}$-inch black-rubber tubing to prevent metallic contact with the boiler. This method of leading the wires out of the boiler is shown in figure 5. It was not satisfactory.

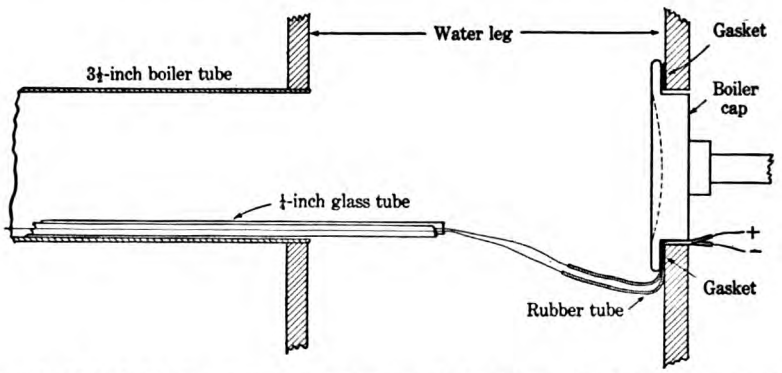

FIGURE 5.—Method of leading thermocouple wires out of boiler in first series of tests. Wires were covered with $\frac{1}{8}$-inch black-rubber tubing and passed out of the boiler between two gaskets.

In the second series of temperature measurements the thermocouple wires were placed in a thick-walled $\frac{1}{4}$-inch glass tubing which passed out of the boiler through a brass stuffing box fitted into the handhole cover. The hole in the tubing was so small and was so nearly filled with the wire that the leakage of steam and water was small. This arrangement of couples is shown in figure 6.

The glass tubing was attacked by the boiler water and gradually became soft and opaque, and disintegrated after about 5 days' usage under running condition of boiler. In later experiments small porcelain tubes were used and the boiler water and steam did not affect these appreciably.

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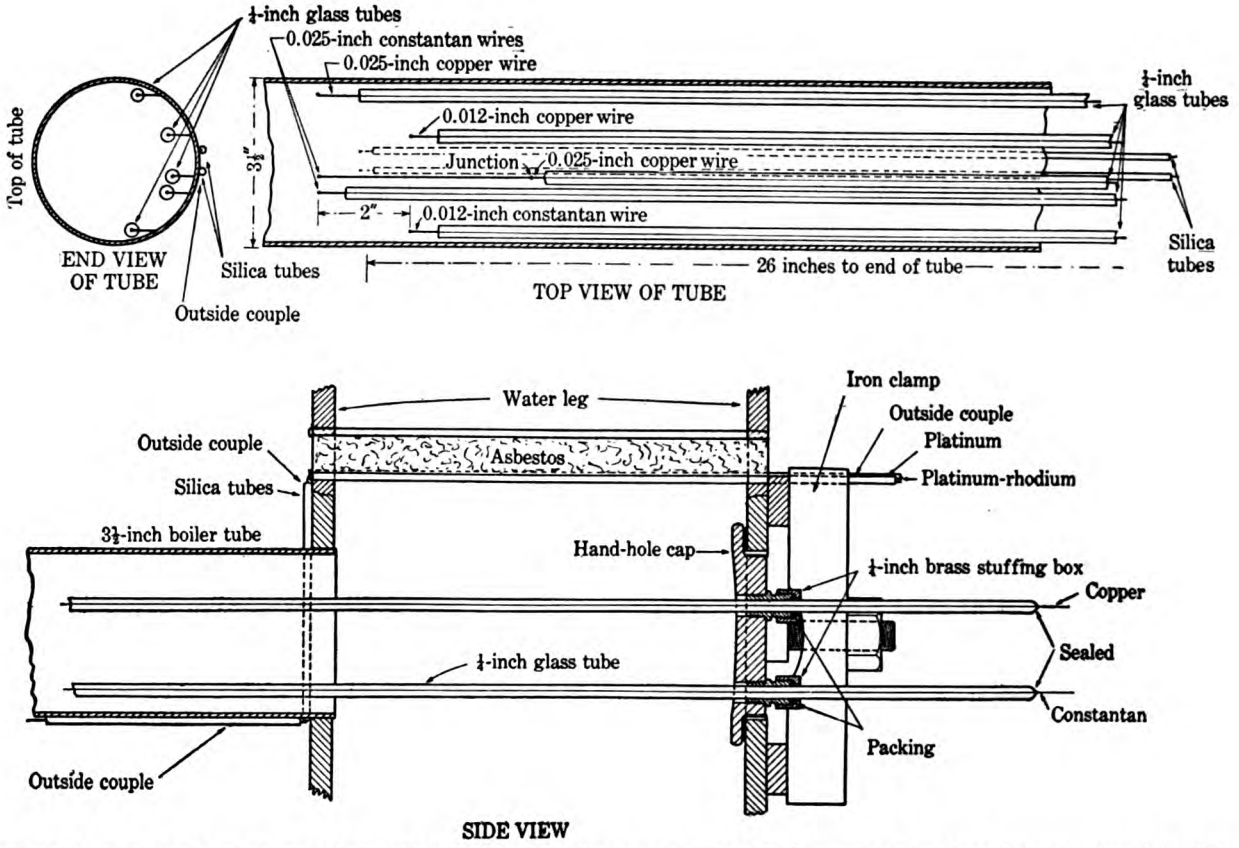

FIGURE 6.—Position of thermocouples in boiler tube and method of leading wires out of the boiler in second series of tests. Wires were placed in a thick-walled ¼-inch glass tubing which passed out of the boiler through brass stuffing box. The thickness of wires and the kind of metal is indicated.

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MEASUREMENT OF TEMPERATURE DIFFERENCE BETWEEN TUBE AND BOILER WATER.

The method of measuring the temperature difference between the inside surface of the boiler tube and the boiler water is shown diagrammatically in figure 7. The arrangement of the wires of the couple as it was used in the boiler is shown in figure 8.

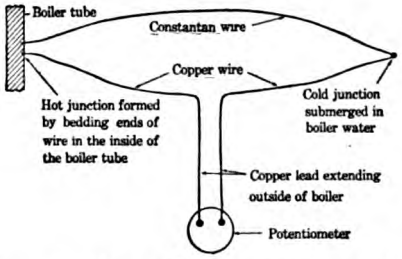
Boiler tube
Constantan wire
Copper wire
Hot junction formed by bedding ends of wire in the inside of the boiler tube
Cold junction submerged in boiler water
Copper lead extending outside of boiler
Potentiometer

FIGURE 7.—Diagram showing method of measuring the difference of temperature between the water-side surface of the boiler tube and the boiler water.

The differential couple consisted of a short piece of constantan wire, one end of which was embedded in the boiler tube; the other end being joined inside the tube to a copper wire, which extended out of the boiler and was used as the other lead of the couple. Thus there was formed a copper-constantan couple with the hot junction in the inside surface of the boiler tube, and the cold junction in the boiler water. The potential set up in the couple was of course due to the difference of temperature between the two junctions and therefore was a measure of the temperature difference between the inside surface and the boiler water.

Referring to figure 8, when the differential wire *a* was used with constantan wire *b*, a copper-constantan couple was formed, the hot

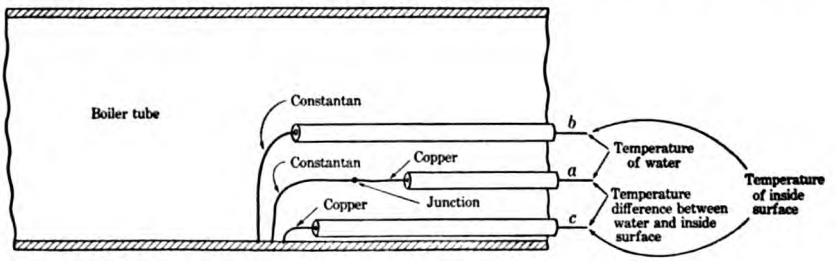

FIGURE 8.—Arrangement of the wires of thermocouples inside boiler tube. By combining two wires three temperatures were obtained, namely: Wires *a* and *b* gave the temperature of water, wires *b* and *c* gave the temperature of inside surface; wires *a* and *c* gave the temperature difference between water and inside surface.

junction of which was in the boiler water and the cold junction at any convenient place and at any convenient temperature outside the boiler. The connection of the short piece of constantan wire of *a* with that of *b* through the metal of the boiler had no electrical effect. Thus the wires *a* and *b* gave the temperature of the boiler water. By using the wires *b* and *c* the temperature of the inside surface of the boiler tube was obtained.

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The temperature of the boiler water was measured independently of these wires with the couple shown in figure 9.

The couple was made by placing a constantan wire in a ¼-inch copper tube and fusing them together at one end. Beyond the junction formed by this fusion the constantan wire was insulated from the copper tube by a glass tubing slipped over the wire and into the copper tubing. This couple was inserted into any place in the boiler tube through a stuffing box fitted into a hand-hole cap, as shown in the figure. This construction of the couple prevented any disturbance from galvanic action and electric leakage through the boiler water. It is shown in the charts that the results obtained with this tube couple checked very closely the results obtained with wires *a* and *b* (fig. 8).

RESULTS OF TEMPERATURE MEASUREMENTS.

During the first series of experiments in measuring the temperature of boiler tubes many difficulties were met. Most of the couples

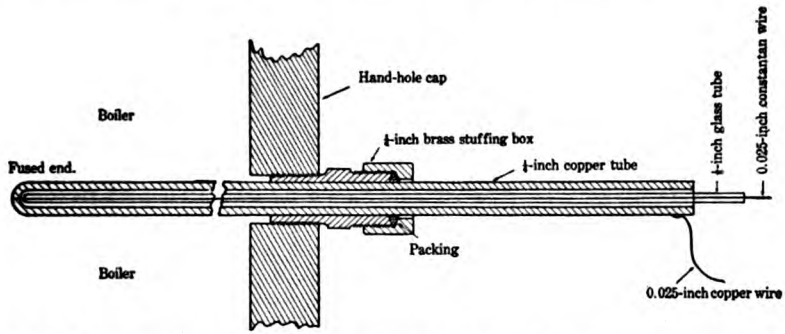

FIGURE 9.—Thermocouple for measuring the temperature of boiler water. The couple is made of ¼-inch copper tube and a constantan wire which is placed inside of the tube and insulated from it by glass tubing.

broke or became useless in other ways before any readings could be made. Figures 10 and 11 show the reliable results that were obtained with this series of experiments. These two figures give the temperature of the outside surface of the top boiler tube as measured by the copper-constantan thermocouple. The position of the couple is shown in figure 2. With this temperature is plotted the temperature of the steam as obtained from steam pressure, the temperature of the gases entering the boiler as measured with an optical pyrometer at section H (fig. 2) of the long combustion chamber, and the temperature of flue gases measured by a thermocouple. The steam-pressure measurements are correct within 2 pounds so that the steam temperature is correct within about 1° F.

The noteworthy feature of these figures is the manner in which the temperature of the outside surface of the tube follows the temperature

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of the steam and is little affected by the temperature of the gases. The difference between the temperatures of the outside surface of the top boiler tube and the steam is only 3 or 4 degrees. While these experiments were in progress the water evaporated by the boiler was measured and the average rate of evaporation per square foot of heating plate is given in the figure. The readings on the thermo-

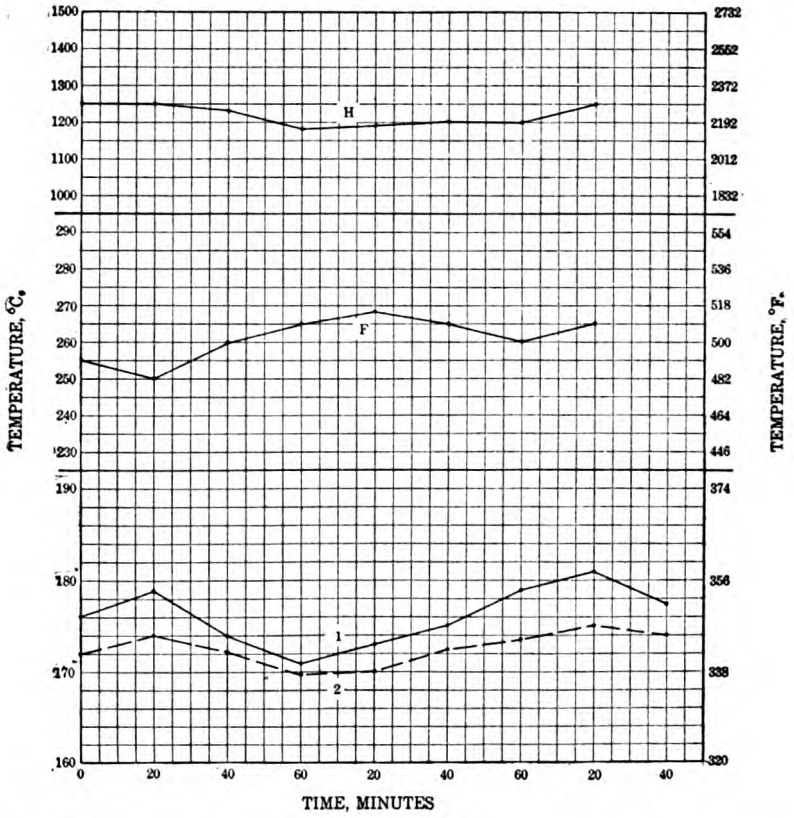

FIGURE 10.—Results of first series of temperature measurements taken December 9, 1913. H, temperature of gases entering boiler; F, temperature of gases leaving boiler; No. 1, temperature of the gas-side surface of a boiler tube in the top row at a place where the gases leave the boiler; No. 2, temperature of steam. Average rate of equivalent evaporation, 2.3 pounds per square foot of gas-side surface per hour.

couple were made with a galvanometer having a resistance of 462 ohms.

The data obtained on the second series of experiments are more complete, although only the temperature of a tube in the lowest row was measured. The position of the thermocouples is shown in figures 2 and 6. The results of this series of experiments are given in figures 12 to 16, inclusive. When studying these results one should remember that the couples were situated at a place where the hot gases first

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struck the boiler tube and therefore where the boiler temperature differences were greatest.

In figures 12 to 16, curve 1 shows the temperature of the gas-side surface of the boiler tube as measured by the platinum and platinum-rhodium couple; curve 2 gives the temperature of the water-side surface of the tube as measured with the copper-constantan couple; curve 3 shows the temperature of steam in boiler obtained from pressure of steam, and curve 4 represents the temperature of water in the tube as measured with the copper tube thermocouple. The small circles near curve 4 represent readings obtained with the couple

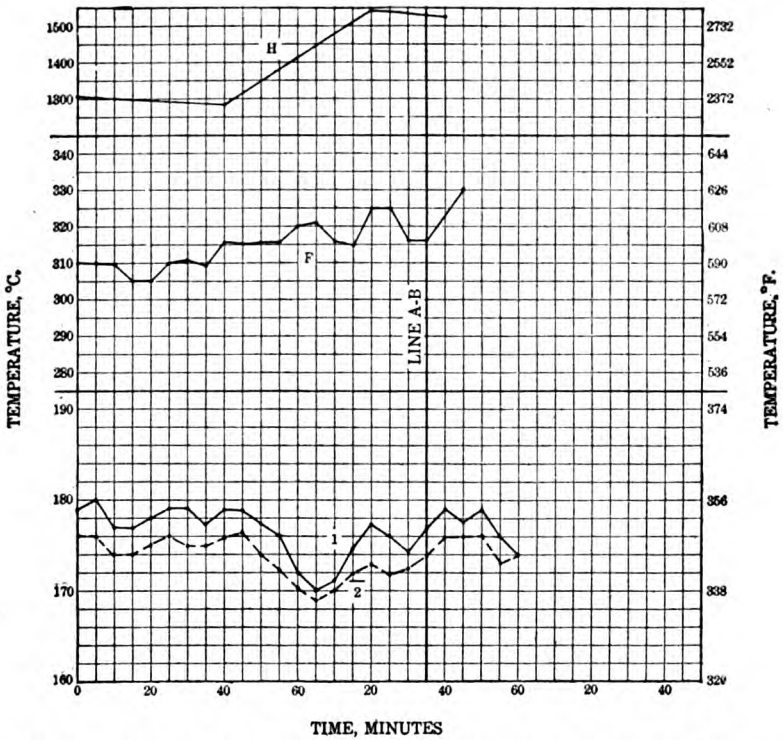

FIGURE 11.—Results of first series of temperature measurements taken November 11, 1913. H, temperature of gases entering boiler; F, temperature of gases leaving boiler; No. 1, temperature of the gas-side surface of a boiler tube in the top row at a place where the gases leave the boiler; No. 2, temperature of steam. Average rate of equivalent evaporation, 1.7 pounds per square foot of gas-side surface per hour.

formed by wires *a* and *b*, figure 8. Attention is called to the fact that the temperatures indicated by these small circles follow closely the temperatures obtained with the copper tube-constantan wire couple, which was not affected by electrical leakage nor galvanic action. Curve 5 shows the temperature difference between the water and the water-side surface of the tube as measured by the differential couple formed by wires *a* and *c* of the couple shown in figure 8, thus checking the

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readings obtained with the wire couples which were exposed to the boiler water. Curve 6 is obtained by subtracting the values of curve 4 from those of curve 2. In general, the last two curves are close together. That there should be some difference can be expected from the fact that the readings of the temperature taken with the different couples were not simultaneous but consecutive. Curve H shows the temperature of the gases entering the boiler as measured with an optical pyrometer at section H, shown in figure 2. Curve F indicates the temperature of gases leaving the boiler's heating plates,

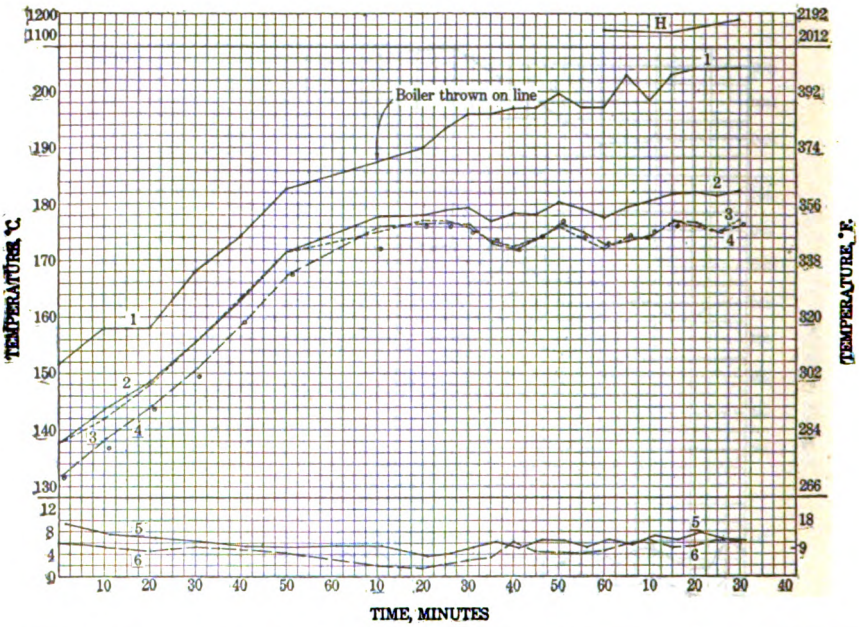

FIGURE 12.—Results of second series of temperature measurements taken August 3, 1914. H, temperature of gases entering boiler; No. 1, temperature of gas-side surface of a boiler tube in the lowest row at a place where the hot gases enter the boiler; No. 2, temperature of the water-side surface of the same tube; No. 3, temperature of steam, obtained from pressure; No. 4, temperature of boiler water, obtained with the copper-tube thermocouple; small circles near curve 4, readings obtained with wires *a* and *b* of couple shown in figure 8; No. 5, difference between the temperatures of the water-side surface and those of the boiler water, obtained with wires *a* and *c* of couple shown in figure 8; No. 6, difference obtained by subtracting the values of curve 4 from those of curve 2. Average rate of equivalent evaporation, 2.8 pounds per square foot of gas-side surface per hour.

measured with a thermocouple in the uptake. All readings of the temperature of the tube surfaces and of the water were made with a portable Leeds & Northrup potentiometer.

The steep part of the curves in figure 12 shows the increase in temperatures of the tube and the boiler water when the boiler was being heated. During the heating the temperature of the water in the tube was seemingly a few degrees lower than the temperature of the steam. But as the steam pressure approached that in the main line, the temperature of the water became the same as that of the

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steam, and the temperature difference between the inside surface of the tube and the boiler water became smaller. Figures 12 to 15, inclusive, all show that the temperatures of both surfaces of the tube followed the temperature of the water in the tube, and were little affected by the temperature of the gases entering the boiler.

TEMPERATURE DROP ALONG THE PATH OF HEAT TRAVEL.

Figure 16 shows the temperature drop along the path of heat travel from the hot gases into the boiler water. The diagram on the left represents the temperatures at a place where the hot products of combustion enter the boiler, the temperatures being those

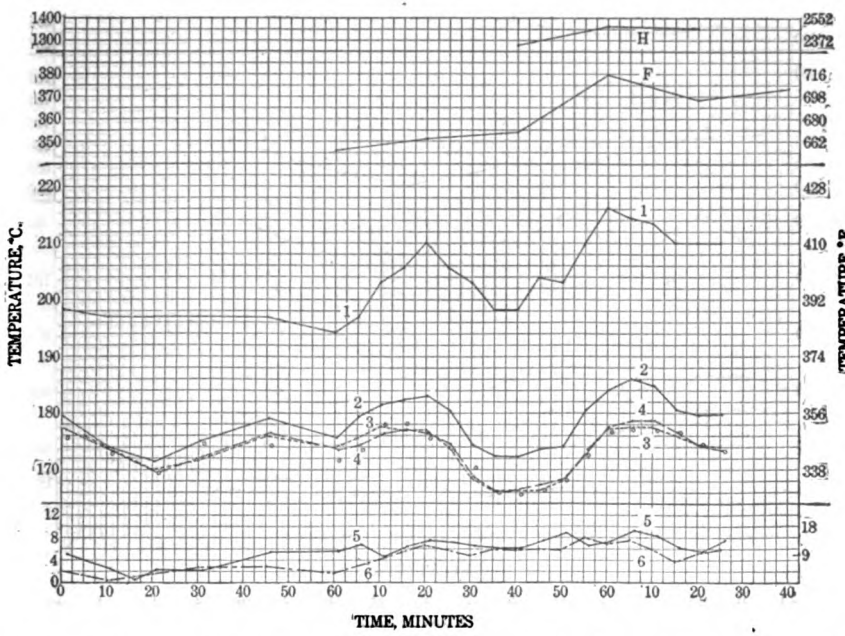

FIGURE 13.—Results of second series of temperature measurements taken August 4, 1914. H, temperature of gases entering boiler; F, temperature of gases leaving boiler; No. 1, temperature of the gas-side surface of a boiler tube in the lowest row at a place where the hot gases enter the boiler; No. 2, temperature of the of the water-side surface of the same tube; No. 3, temperature of steam, obtained from pressure; No. 4, temperature of boiler water, obtained with the copper-tube thermocouple; small circles near curve 4, readings obtained with wires *a* and *b* of thermocouple shown in figure 8; No. 5, difference between the temperatures of the water-side surface and those of the boiler water, obtained with wires *a* and *c* of couple shown in figure 8; No. 6, difference obtained by subtracting the values of curve 4 from those of curve 2. Average rate of equivalent evaporation, 3.2 pounds per square foot of gas-side surface per hour.

given in figure 14 on the vertical line AB. The diagram on the right represents the temperature drop along the path of heat travel at a point where the hot gases leave the boiler, the temperatures being the same as given in figure 10 on line AB.

The striking feature of the two diagrams, particularly of the one on the left, is the large temperature drop from the hot gas to the gas-side surface of the tube and the small drop from this surface to

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the boiler water. This diagram resembles very much a diagram which was constructed on data compiled from purely theoretical considerations, and published as figure 46 [a] of Bulletin 18. The large temperature drop from the gas to the metal of the tube indicates that the resistance to the flow of heat is high, and that this part of the heat path is responsible for the slow rate of heat transmission into steam boilers. When the heat has once reached the surface of the boiler tube, it passes into the boiler water easily. In water-tube boilers, as long as the inside surface of the tube is kept free from scale, oil, and other deposit, the metal of the boiler will transmit

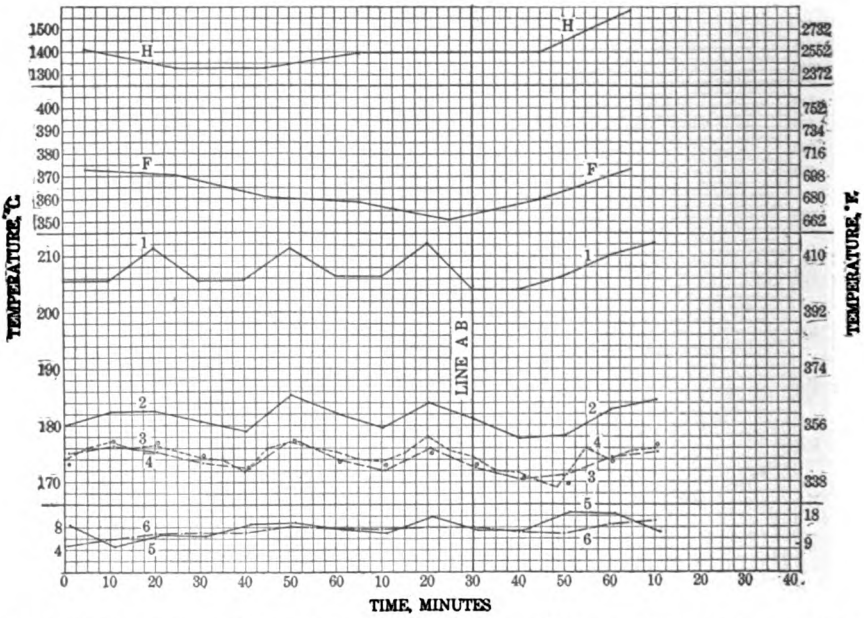

FIGURE 14.—Results of second series of temperature measurements taken August 4, 1914. H, temperature of gases entering boiler; F, temperature of gases leaving boiler; No. 1, temperature of the gas-side surface of a boiler tube in the lowest row at a place where the hot gases enter the boiler; No. 2, temperature of the water-side surface of the same tube; No. 3, temperature of the steam obtained from pressure; No. 4, temperature of boiler water obtained with the copper-tube thermocouple; small circles near this curve, readings obtained with wires *a* and *b* of couple shown in figure 8; No. 5, difference between the temperatures of the water-side surface and those of the boiler water, obtained with wires *a* and *c* of couple shown in figure 8; No. 6, difference obtained by subtracting the values of curve 4 from those of curve 2. Average rate of equivalent evaporation, 4.4 pounds per square foot of gas-side surface per hour.

easily all the heat that can ever be imparted to it by the hot gases without being overheated.

However, in horizontal return tubular boilers with thick shells, if the rivet heads on the seams are exposed to hot gases the rivet heads may become heated enough to affect the strength of the metal. This may happen particularly if mud and scale are allowed to accumulate

[a] Kreisinger, Henry, and Ray, W. T., The transmission of heat into steam boilers: Bull. 18, Bureau of Mines, 1912, p. 106.

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on the sheets. Thus if the shell is made of $\frac{5}{8}$-inch steel plate the extreme distances between the gas and water surfaces of the rivet head may be 2 inches, or 16 times as much as the thickness of the tube in a Heine boiler. Now, if in the Heine boiler the temperature drop through the tube is 25° C., in the horizontal tubular boiler it may be 16 times 25° C., or 400° C., which drop would bring the temperature of the heads of the rivets exposed to hot furnace gases to about 575° C. This is dull red heat, which might be sufficient to weaken the seam.

In general, it can be said that it is not a question of how much heat a boiler's heating plate can transmit, but how much heat can be

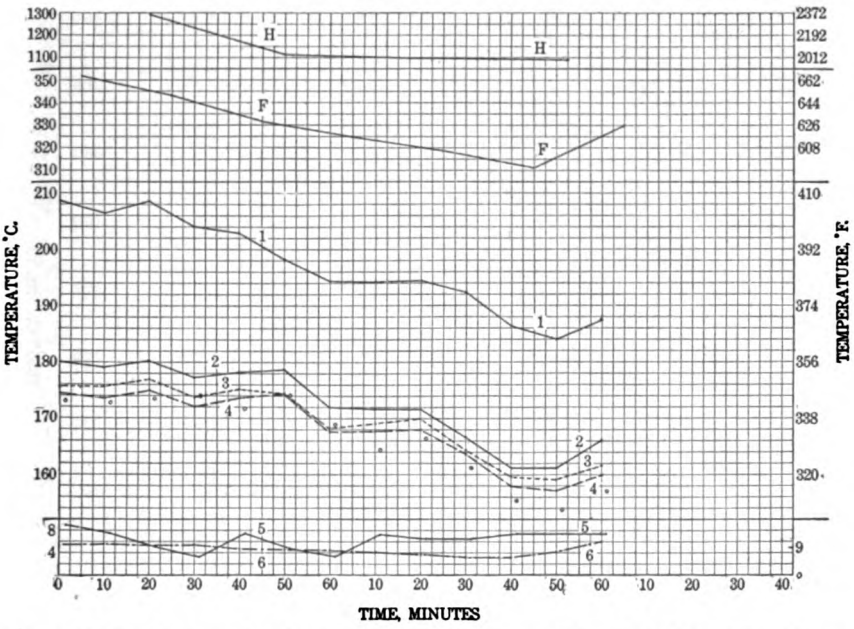

FIGURE 15.—Results of second series of temperature measurements taken September 1, 1914. H, temperature of gases entering boiler; F, temperature of gases leaving boiler; No. 1, temperature of the gas-side surface of a boiler tube in the lowest row at a place where the hot gases enter the boiler; No. 2, temperature of the water-side surface of the same tube; No. 3, temperature of the steam, obtained from pressure; No. 4, temperature of boiler water, obtained with the copper-tube thermocouple; No. 5, difference between the temperatures of the water-side surface and those of the boiler water, obtained with wires *a* and *c* of couple shown in figure 8; No. 6, difference obtained by subtracting the values of curve 4 from those of curve 2. Average rate of equivalent evaporation, 3.36 pounds per square foot of gas-side surface per hour.

imparted to it by the hot gases. The heat conductivity of iron is so high that only small difference in temperature is needed on the two sides of the heating plate to transmit heat at the rate of one boiler horsepower per square foot of heating plate.

The ability of the boiler water to take heat away from the heating plate is so great that only a very small temperature drop is necessary to transmit the heat from the plate to the water. These facts prove

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that in steam boilers it is the gas-side surface of the heating plate that counts; the water-side surface has very little effect on the rate of heat transmission.

From the shape of the lines forming the temperature gradient it is apparent that no single equation based on temperature only can be

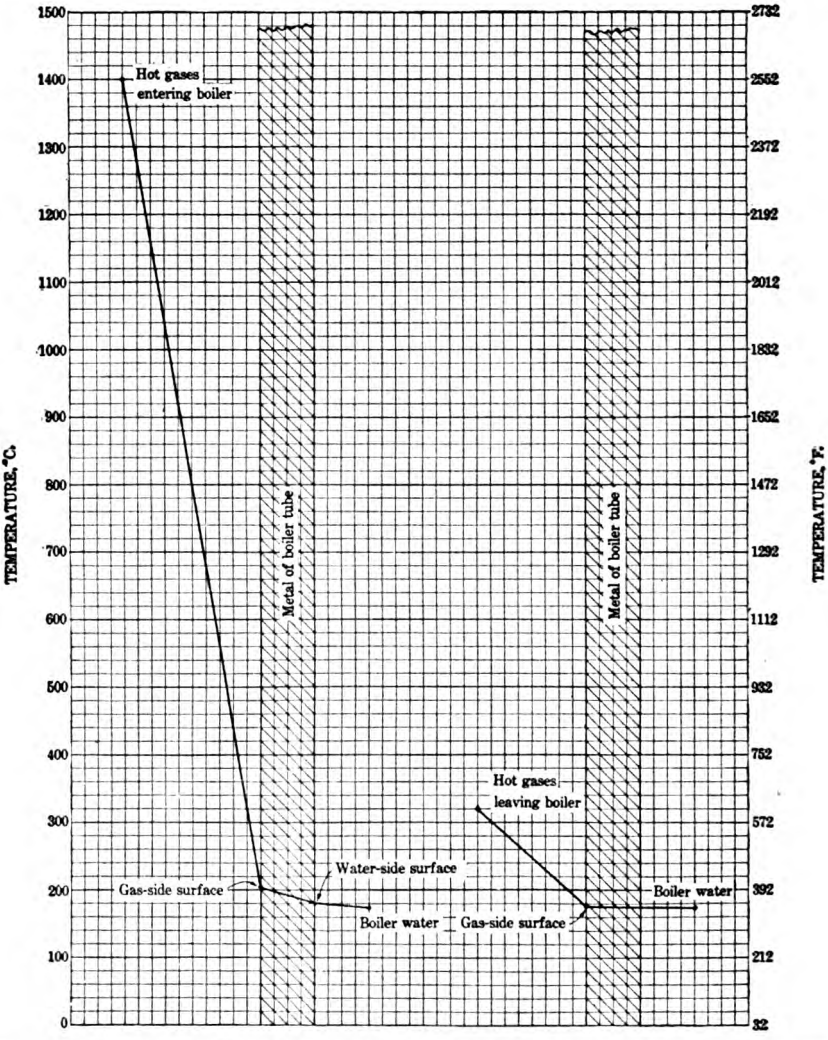

FIGURE 16.—Temperature drop along the path of heat travel from the hot gases into the boiler water. Diagram on left, temperature drop at place where hot gases enter boiler: temperatures same as given on line AB, figure 14. Diagram on right, temperature drop at place where gases leave boiler; temperatures same as given on line AB, figure 10. In these diagrams the horizontal distances have no significance.

made to express the rate of heat transmission from the hot gases into the boiler water. The equation given in some textbooks, which states that the rate of heat transmission is proportional to the square of the temperature difference between the hot gases and the boiler water, is

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only roughly approximate and is practically worthless for steam-boiler problems.

TEMPERATURE DROP ALONG THE PATH OF GASES.

From the temperatures plotted in figure 16 a chart can be compiled which gives approximately the temperature drop of the gases

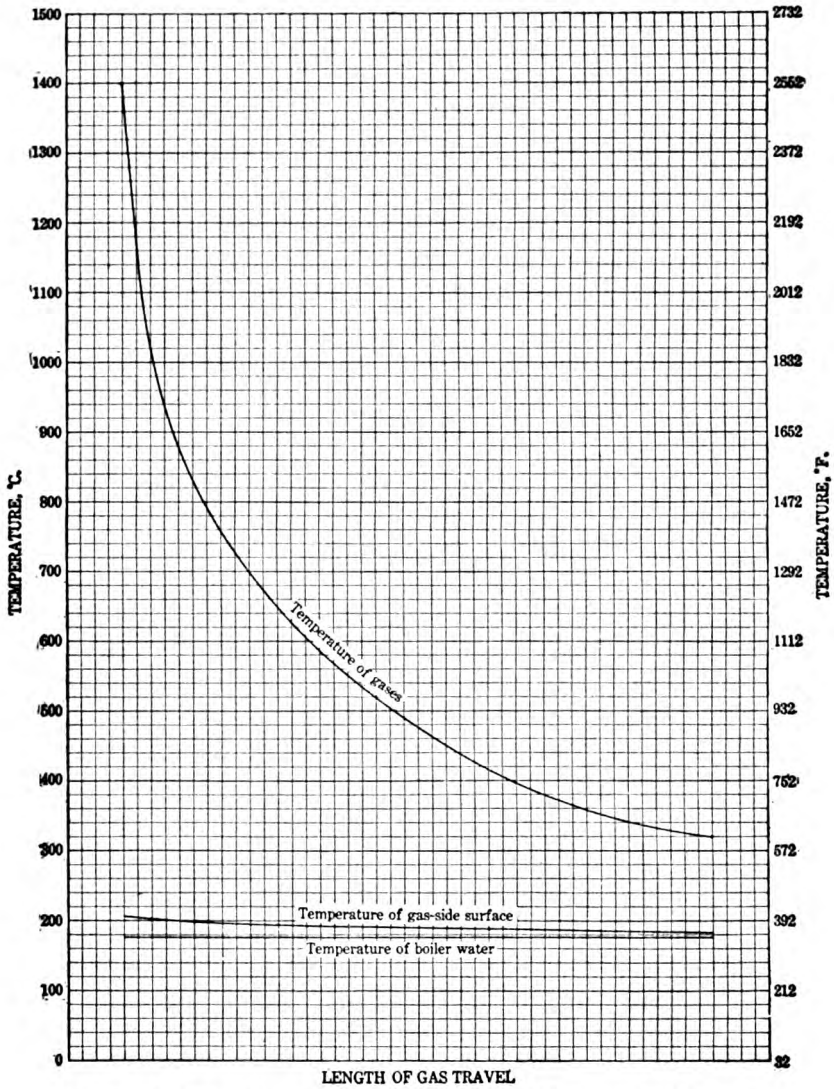

FIGURE 17.—Curves showing probable temperature drop along the path of the gases.

and of the gas-side surface of the heating plate along the path of the gases as they pass over the heating plates of a boiler. Such a chart is shown in figure 17.

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The curve representing the temperature of the gases is logarithmic and is affected by the area of the cross section of the gas passages between the tubes of a water-tube boiler and by the size of the tube in a fire-tube boiler. The shape of the curve representing the temperature of the gas-side surface is no doubt similar to the curve representing gas temperature. The temperature of the boiler water is very nearly constant throughout the boiler; therefore, in the chart it is represented by a straight horizontal line.

CAUSES OF UNEQUAL TEMPERATURE DROP ALONG THE PATH OF HEAT TRAVEL.

In the diagram at the left in figure 16 the large temperature drop from the hot gases to the gas-side surface of the tube, and the small temperature drop from this surface to the water are due mainly to the low heat capacity of gas and the high heat capacity of water. The volume of 1 pound of furnace gas at a temperature of 2,552° F. (1,400° C.) is approximately 65 cubic feet. The volume of 1 pound of boiler water at a steam pressure of 100 pounds is about 0.017 cubic foot. Therefore, the water is $\frac{65}{0.017}=3{,}800$ times as dense as the gases. Even if it is assumed that the gases are cooled 500° F. by the short contact with the boiler tube, the quantity of heat given off by a pound of the gases is 500 times 0.24, or 120 British thermal units. On the other hand, 1 pound of water is capable of absorbing about 900 British thermal units, without rise of temperature, by changing into steam. As the water is 3,800 times as dense as the furnace gases, the relative heat capacity of the same volumes of the gases and the boiler water is as 120 is to 900 times 3,800, or the heat capacity of gases is to the heat capacity of boiler water as 1 is to 28,500. Even if the effective surface on the water side of the tube is reduced to one-fourth by the presence of steam bubbles, the advantage of the water compared with the gases is considerable.

THE RATE OF HEAT CONDUCTION THROUGH THE BOILER TUBE.

For the temperature drop through the tube, as shown in the diagram at the left in figure 16, the rate of heat conduction through the tube at the point where the temperatures are measured can be computed as follows:

In the Smithsonian tables[a] the average heat conductivity of iron at a temperature of 100° to 200° C. is about 0.12. This means that through an iron plate 1 centimeter thick 0.12 small calories are transmitted per second through each square centimeter of area for every degree centigrade of temperature difference between the two surfaces of the plate. This figure is equivalent to 2,300 British thermal units

[a] Fowle, F. E., Smithsonian Physical Tables, 1914, p. 205..

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per hour per square foot of area when the iron plate is one-eighth of an inch thick and the difference of temperature between the two surfaces is 1° F. As the difference of temperature in the two surfaces of the Heine boiler tube where the hot gases enter the boiler is 23° C., or 41.5° F., the rate of heat conduction is 2,300 times 41.5, or 95,400 British thermal units per hour per square foot of area. This is approximately 2.8 boiler horsepower per square foot of heating plate, or 1 boiler horsepower per 0.357 square foot of heating plate.

If the fact be considered that locomotive fire boxes with heating plates three-eighths of an inch thick and receiving heat only by radiation, produce on the average 1 boiler horsepower on one-half square foot of heating plate, the figure 0.357 square foot of heating plate per boiler horsepower is not high.

SUMMARY OF DEDUCTIONS.

The most noteworthy feature shown by the results of these temperature measurements is that the temperature of the boiler tube is within 10° to 20° C., the same as that of the boiler water, and that the temperature of the tube is affected very little by the temperature of the hot gases, but follows the temperature of the boiler water.

As the temperature drop along the path of heat travel is nearly proportional to the resistance to heat travel, the resistance appears to be very high from the hot gases to the gas-side surface of the tube and very low from this surface to the boiler water. This fact indicates that a boiler tube can transmit very easily all the heat that can ever be imparted to it by the hot gases, and that as long as the tubes are kept free from scale, oil, and other deposit and filled with water it is impossible to overheat the tubes, no matter how hard the boiler is worked.

The slow part in the path of heat travel is from the hot gases to the boiler tube. It is this part of the path that is responsible for the slow rate of heat transmission in boilers as now designed and operated. Anything that will increase the rate of heat impartation by the hot gases to the boiler tube will almost directly increase the rate of working of the boiler. This is an important fact and should be kept in mind by the designer when designing a boiler which is to be operated at high capacity.

DISCUSSION OF METHODS EMPLOYED.

There are several questions that may be asked regarding the correctness and the accuracy of the method employed in measuring the temperatures of the surfaces of heating plate. The principal questions are:

(*a*) Is the hot junction formed by embedding the two wires of the couple separately into the metal of the tube the same as when the two wires are in direct contact with each other?

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(*b*) By embedding the ends of the thermocouple wires into the metal of the tube is the junction formed at the surface of the tube or within the metal at the ends of the thermocouple wires?

(*c*) Is the measurement of the temperature of the water-side surface of the tube affected by leakage of electric current through the boiler water, or

(*d*) By galvanic action, the two wires acting as electrodes and the boiler water as electrolyte of a galvanic battery?

(*e*) In measuring the temperature of the gas-side surface of the heating plate is not heat conducted by the thermocouple wires to the junction, thus causing the temperatures indicated by the couple to be too high? On the water side, is not the reverse of this process taking place and causing the temperatures indicated to be too low?

EMBEDDING WIRES SEPARATELY DOES NOT AFFECT HOT JUNCTION.

(*a*) Is the hot junction formed by embedding the two wires of the couple separately into the metal of the tube the same as when the two wires are in direct contact with each other?

Calibration shows that the junction formed by embedding the wires separately into a metal is the same as when the two wires come in direct contact. A short reflection on the principles of thermocouples will convince one that this should be so. There is a source of electromotive force where the copper wire joins the iron plate and another source where the constantan wire joins the plate. When both of these joints are at the same temperature, the algebraic sum of the two electromotive forces is the same as the electromotive force from copper to constantan at the temperature in question. Therefore, as long as the two ends of the thermocouple wires are electrically connected and this connecting piece of metal is at the same temperature at the points of junction with the thermocouple wires, the junction is just the same as if the thermocouple wires were in direct contact. The fact is that whenever a thermocouple is used with a millivoltmeter or a potentiometer for measuring temperatures the cold junction is never made by direct contact of the thermocouple wires themselves, but by means of a long wire extending through the coil of the instrument, otherwise the temperature could not be measured. There is no reason why the hot junction of a couple can not be formed in a similar way as the cold junction. This feature is illustrated by the three diagrams in figure 18.

Diagram A shows a thermocouple, both junctions of which are made by direct contact of the two wires of the couple. This arrangement of the junctions is not practical with most thermocouples, inasmuch as it makes the measurement of the electric potentials difficult, if not impossible.

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Diagram B shows a thermocouple having the hot junction made by direct contact of the two wires, but the cold junction is made through a copper wire which connects the couple to a potentiometer. This is the most common arrangement of thermocouple junctions.

Diagram C shows a thermocouple in which both junctions are indirect. The hot junction, like the cold junction, is made through a piece of metal. These connecting pieces of metal may be of copper, iron, or any other metal. As long as the connecting metal is at the same temperature at the points where it comes in contact with the thermocouple wires the junction is electrically the same as if the thermocouple wires were themselves in direct contact.

HOT JUNCTION IS FORMED AT SURFACE OF EMBEDDING METAL.

(*b*) By embedding the ends of the thermocouple wires into the metal of the tube, is the junction formed at the surface of the tube or within the metal at the ends of the thermocouple wires?

The electrical potential impressed on the thermocouple wires extending from the metal of the tube is a function of the temperature at the surface of the tube and not of the temperature within its metal at the ends of the thermocouple wires.

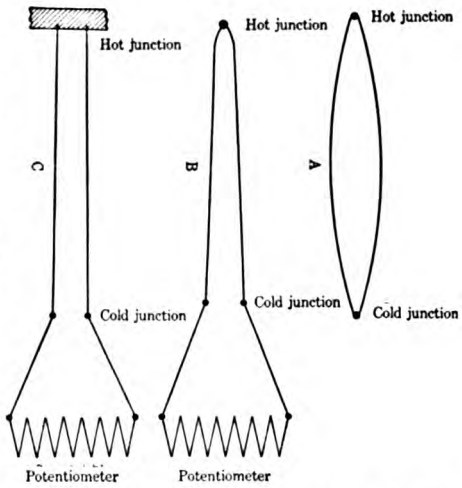

FIGURE 18.—Diagrams showing methods of forming junctions on thermocouples. A, both junctions made by direct contact of the thermocouple wires; B, hot junction formed by direct contact of thermocouple wires, cold junction formed by connecting thermocouple wires with copper wires to a potentiometer; C, hot junction formed by embedding thermocouple wires in an iron plate, cold junction formed by connecting with copper wires to potentiometer.

Whatever potential difference is set up in the part of the wires embedded in the plate, due to difference of temperature, is retained in the metal plate because the metal of the plate short-circuits the thermocouple wires and no potential is impressed on the wires outside the plate. This fact can be shown best by the diagram given in figure 19.

The diagram shows a cross section of a heating plate and two thermocouple wires embedded in it. Assume that the ends of the wires are at temperature T, which is higher than the temperature t at the surface of the plate. As the embedded parts of the two wires are connected along their entire length by intervening metal, there is a

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hot junction formed at the ends of the wires and a cold junction near the surface of the plate. On account of the difference between temperatures T and t an electric current flows as indicated by the arrows. The resistance through the metal at the surface of the plate being zero in comparison to the large resistance of the galvanometer placed between the outside ends of the thermocouple wires, all the current passes through the plate near the surface and none through the galvanometer; consequently the effect of the difference between T and t is not shown on the galvanometer. The electrical potential causing a current to flow through the galvanometer is due entirely to the temperature difference between t and t_1, and is therefore the measure of this temperature difference.

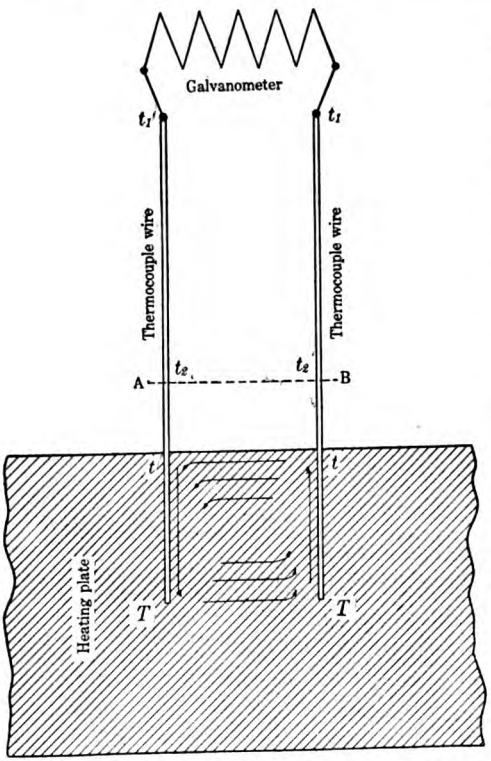

FIGURE 19.—Diagram to show that hot junction is formed at the surface of the metal into which the thermocouple wires are embedded, and not at the ends of the wires within the metal.

In a similar way, if a large wire were placed across the thermocouple wires as shown by the dotted line AB in figure 19, all electrical current caused by the difference of temperature between the wire and the heating plate would be discharged through the wire AB owing to its very low resistance, and practically no current would flow through the galvanometer. If the galvanometer would show any current the latter would be due to the temperature difference between the junction formed by the wire AB and the junction at the galvanometer. In other words, this electrical potential would measure the temperature difference $(t_2 - t_1)$.

It is true that not only are the points at T and t sources of electromotive force, but every point of contact along the embedded parts of both wires is a source of electromotive force; however, on account of the electrical connection of these points through the iron plate, this electromotive force is not impressed on the parts of the wires outside the plate.

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EFFECTS OF ELECTRIC LEAKAGE AND GALVANIC ACTION OF BOILER WATER.

(*c*) Is the measurement of the temperature of the water-side surface of the tube affected by leakage of electric current through the boiler water; or

(*d*) By galvanic action, the two wires acting as electrodes and the boiler water as electrolyte of a galvanic battery?

In order to determine what effects upon the thermocouples in the measurement of the temperature were caused by the surrounding boiler water a calibration was made by means of the apparatus shown in figure 20.

DESCRIPTION OF APPARATUS, AND RESULTS.

Two copper and two constantan wires were peened into an iron strip (as shown in fig. 20), thus forming two thermocouples. The

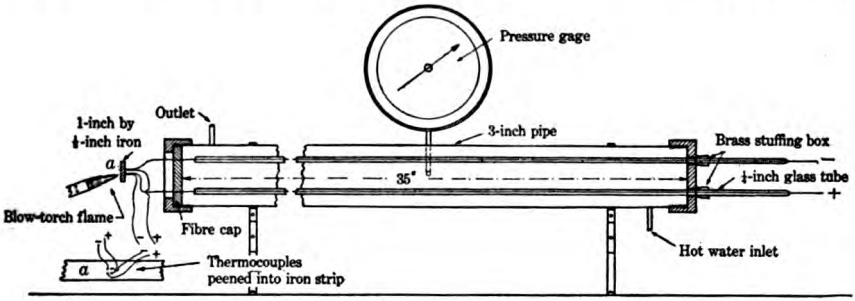

FIGURE 20.—Apparatus for calibration of thermocouples immersed in boiler water. Two couples are embedded in the same iron plate. The leads of one of the couples pass through the water in the apparatus and the leads of the other are in air. The readings of the two couples are compared.

leads of one thermocouple were taken through the 3-inch pipe and brought out through the cap in a manner similar to the method used in bringing out the thermocouple wires from the boiler. This pipe was of such a length that the leads were surrounded by water for about the same distance as in the boiler tube. The leads of the other thermocouple were in air. Before any water was run into the pipe a calibration was made, showing that the two thermocouples read exactly alike. Hot water from the boiler was made to pass through the apparatus by means of the connections shown in figure 21, so that the same water and pressure were used as when the thermocouples were read in the boiler tube. The water flowing through the boiler tube of figure 20 forces itself into funnel *b* forming a circuit through the calibration apparatus and ending with the pipe *c*.

It was found that the readings of the thermocouple in the tube was 0.12 millivolt to 0.15 millivolt too high, equivalent to prac-

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tically 3° C. Hence 3° C. has been subtracted from the temperatures indicated by actual measurement.

DISCUSSION OF RESULTS.

The cause for the "boosting" effect is probably best explained by the diagram shown in figure 22.

As shown by the diagram, the potentiometer, as it takes no current, would always read the potential at C and D. Let G represent the battery as formed by the boiler water and thermocouple leads.

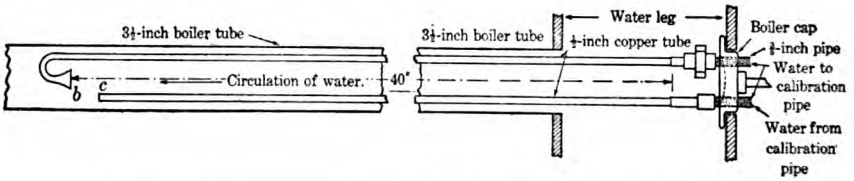

FIGURE 21.—Method of causing boiler water to circulate through calibration apparatus.

Either of two conditions might exist as shown by the arrows E and F. If the potential of A were greater than that of G, or if the polarity of G were reversed with reference to A, a current would flow in the direction indicated by arrow E; thus the voltage between C and D would have been lower than AB, so that leakage would have occurred through the boiler water. If the galvanic action were greater than the potential of A and in such a direction as to cause a current to flow in the direction indicated by arrow F the voltage of CD would be greater than AB and boosting would have occured.

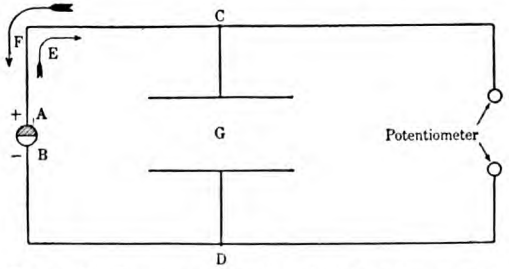

FIGURE 22.—Diagram of galvanic action of the thermocouple wires immersed in boiler water.

This latter condition was found to fit the case of the copper-constantan thermocouple whose galvanic action in hot water is about 1 volt and is in the same direction as the thermocouple voltage. Due to the high internal resistance of the battery (about 5,000 ohms) not much boosting occurs through the external resistance, which is made up of the wire leads and of the resistance of the thermocouple itself.

Perhaps this small boosting can be made clearer by the use of the following specific case:

In regard to the diagram shown in figure 22 let it be assumed that the internal resistance of the battery G is 5,000 ohms; that the resistance of the leads from C through A and B to D is 0.5 ohm;

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and that the electromotive force of battery G minus that of the thermocouple is 1 volt. Along any closed circuit the potential drop is proportional to the resistance; therefore the potential drop from C through A and B to D, were there no thermocouple action, would be $\frac{1}{5000.5} \times 0.5 = \frac{0.5}{5000.5}$ volt, or 0.1 millivolt.

This means that to discharge the current of the battery G through the thermocouple junction A and B the potential between C and D must be 0.1 millivolt higher than the potential set up by the thermocouple junction; in other words, the potential at C and D is boosted 0.1 millivolt by the battery above the potential of the thermocouple. The electric potential of the couple due to temperature of the boiler tube was about 7 millivolts and was boosted by the galvanic action of the wires and boiler water to 7.12 millivolts. This boosting was determined by calibration, as explained in connection with figures 20 and 21.

Hoskins thermocouples have the polarity of the galvanic action reversed with reference to the thermocouple. Hence great leakage takes place, making them undesirable for such measurements.

EFFECT OF HEAT CONDUCTIVITY OF THERMOCOUPLE WIRES.

(*e*) In measuring the temperature of the gas-side surface of the heating plate is not heat conducted by the thermocouple wires to the junction, thus causing the temperatures indicated by the couples to be too high? On the water side, is not the reverse of this process taking place and causing the temperatures indicated to be too low?

On the gas side of the boiler tube the thermocouple wires undoubtedly do conduct some heat to the junction, thus causing the indicated temperature of the gas surface of the tube to be somewhat higher than the surface temperature normally is. However, the conductivity of the tube is so high and the wires of the couple are so small (0.012 inch in diameter) that the excess in temperature of the junction due to this cause is small. The exact amount of excess can not be stated definitely, but there is a good reason to believe that it is not over one or possibly two degrees, an error which is almost within the limits of accuracy of the method.

On the water side of the boiler tube the thermocouple wires conduct some heat away from the junction, thus causing the temperature of the water-side surface to appear somewhat lower than it is under normal conditions. To determine approximately how much too low the readings are, two couples of the same metals but of different diameters were embedded in the tube; one couple had wires 0.025 inch and the other 0.012 inch in diameter. The larger wires, on account of conducting more heat away from the junction should give readings somewhat lower than the thin wires. However, before any reading could be taken one of the thin wires broke. Readings were

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then taken with one thin wire and a thick wire and these readings were compared with those taken with two thick wires. No difference in reading was detected with the most careful observation. The following table gives a series of alternate readings. The readings were taken within a few seconds of one another.

Results of alternate temperature measurements taken with thick and thin thermocouple wires.

Two thick wires 0.025 inch in diameter.	One thick wire 0.025 inch in diameter and one thin wire 0.012 inch in diameter.	Two thick wires 0.025 inch in diameter.	One thick wire 0.025 inch in diameter and one thin wire 0.012 inch in diameter.
° C.	° C.	° C.	° C.
685	685	670	670
686	686	679	679
672	672	682	685
678	670	689	689
676	678	689	689
685	695	685	686
675	675	690	690

TEMPERATURE OF THE OUTSIDE SURFACE OF A STEAM PIPE.

The method described herein of measuring the temperature of the surfaces of boiler tubes can be applied to many other problems. The authors applied it with success to the measurement of the temperature of the outside surface of a steam pipe when bare and also when covered with a 1-inch layer of magnesia pipe covering. The wires of a copper-constantan couple were embedded into the outside of a 6-inch steam pipe in the manner described in connection with figure 4. The steam pipe was about 40 feet long and was in horizontal position. The couple was placed on the side of the steam pipe as shown in figure 23.

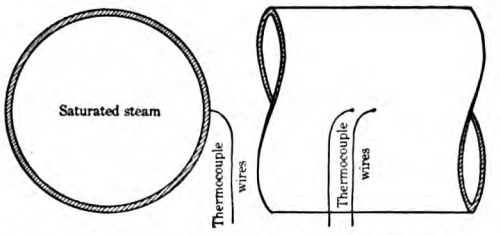

FIGURE 23.—Diagram showing position of thermocouple in steam pipe.

RESULTS OF TEMPERATURE MEASUREMENTS.

The following table gives the results of the temperature measurements. The temperature of the steam was determined from the pressure. The flow of saturated steam through the pipe was about 26 feet per second.

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Results of temperature measurements of covered and uncovered pipe.

Condition of pipe.	Temperature of steam.	Temperature of outside surface of pipe.	Difference of temperature.	Temperature of room.
	° C.	° C.	° C.	° C.
Pipe bare	173.8	173.2	0.6	18
Do	175.8	173.7	2.1	
Do	174.2	173.2	1.0	
Do	173.1	172.7	.4	
Do	174.2	172.7	1.5	
Do	175.1	174.7	.4	
Pipe covered	172.7	172.7	0	20
Do	173.8	173.2	.6	
Do	174.2	173.9	.3	
Do	173.4	173.7	−.3	
Do	173.8	173.8	0	
Do	173.8	173.8	0	

DISCUSSION OF RESULTS.

The results show that the temperature of the outside surface of the pipe is very nearly that of the steam in the pipe. There is no appreciable difference in the temperature of the outside surface whether the pipe is bare or covered with a 1-inch layer of magnesia pipe covering. Therefore the conductivity of the iron in the pipe is so high that only a fraction of a degree of temperature drop between the two surfaces is needed to conduct through the metal all the heat that can be radiated from the outside surface of the pipe under almost any condition; also the rate of heat impartation from the steam to the inside surface of the pipe is so high that the metal is kept at the same temperature as the steam. This is undoubtedly due to the fact that saturated steam can give off a large quantity of heat by condensation without any change in temperature.

From the preceding deductions it follows that in computing the heat losses through pipe coverings the resistance to the heat flow through the metal of the pipe can be dropped out of the problem and only the resistance of the covering material considered. That is, it is safe to assume the inside surface of the covering to be at the same temperature as the steam.

The above deductions hold true only for saturated steam. With superheated steam and hot water, both of which give off heat by drop in temperature, the results would very likely be greatly modified.

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